Magnetospheric Multiscale Mission Attitude Dynamics: Observations from Flight Data

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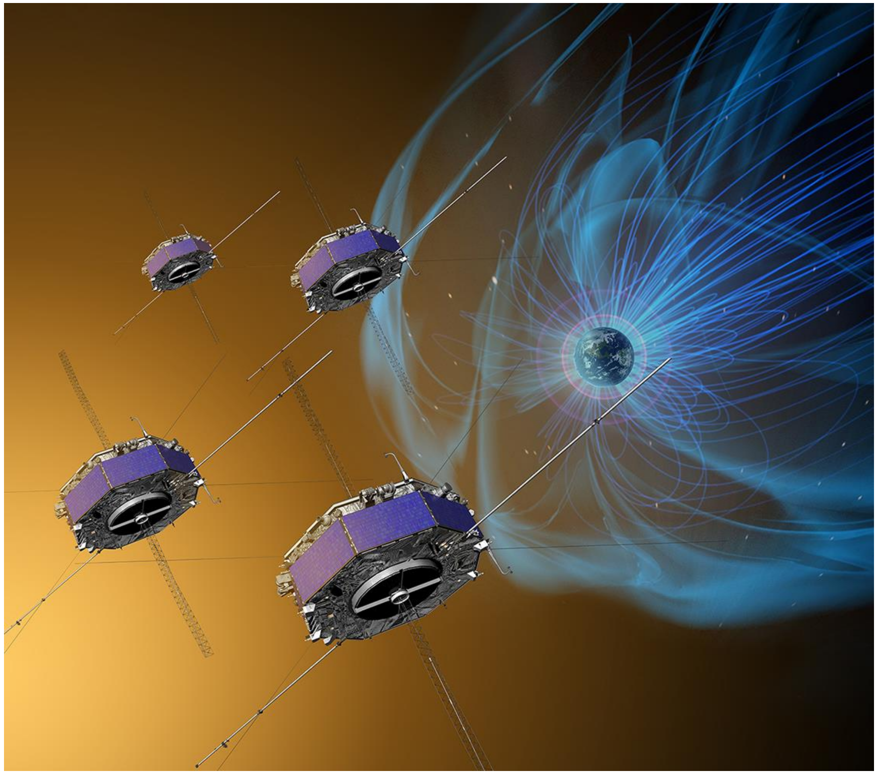
Summary of Presentation

- MMS: four helioscience spacecraft flying in formation
- Spinners (3.05 RPM); 60 m wires
- Thrusters for attitude, orbit control
- Star camera attitude sensors
- Summary of presentation:
  - Spin axis targeting
  - Effects of environmental torques
  - Effects of active potential control device (jets of Indium ions) on observed spacecraft spin rate
  - Derivation of effective thrust
  - Analysis of MMS4 impact event in Feb. 2016, using attitude data



Spin Axis Target

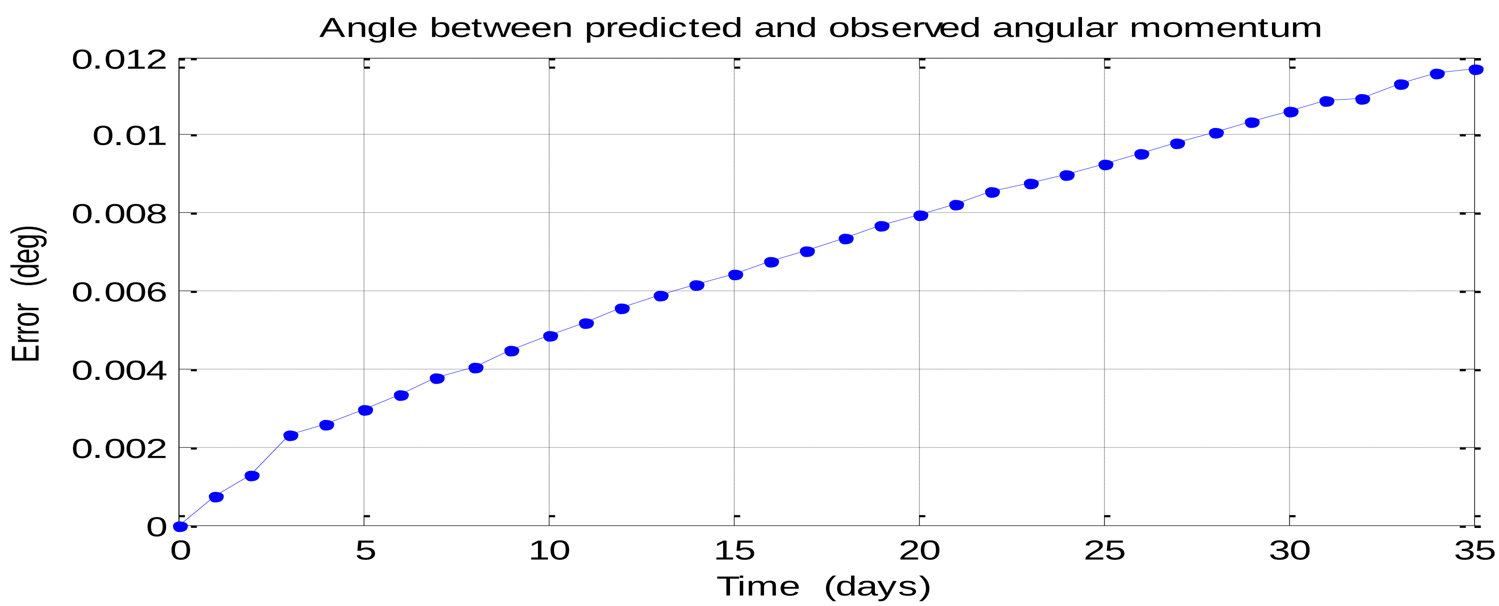
- Spin axis (body *Z*-axis) must be near ecliptic pole
- This attitude ensures sunlight does not fall on upper deck
  - Upper deck illumination would cause emission of photoelectrons that would perturb the local plasma and field measurements
- However, spin axis needs some tilt towards the Sun
  - Tilt prevents shadows from pre-amplifiers on wire booms from crossing the spherical detectors at ends of wire booms
    - Shadows cause momentary interruption of photo-emissive electron cloud around detector spheres, again perturbing field measurements
- Target box for science ops is isosceles trapezoid, roughly 2.5 deg × 2.5 deg with center tipped 3.5 deg toward Sun

Environmental Torques

- MMS Attitude Ground System (AGS) predicts when spin axis will drift to the edge of the target box
  - AGS plans attitude slews to center or to opposite edge of box to maximize time between maneuvers
  - Spin axis drift depends on seasonally changing environmental torques
  - Very rough order-of-magnitude estimates of torques
    - Gravity-gradient: 10^{-4} N-m
    - Solar pressure: 10^{-6} N-m
    - Aerodynamic drag: 10^{-7} N-m
  - So, only gravity-gradient (GG) torque is used in AGS predictions

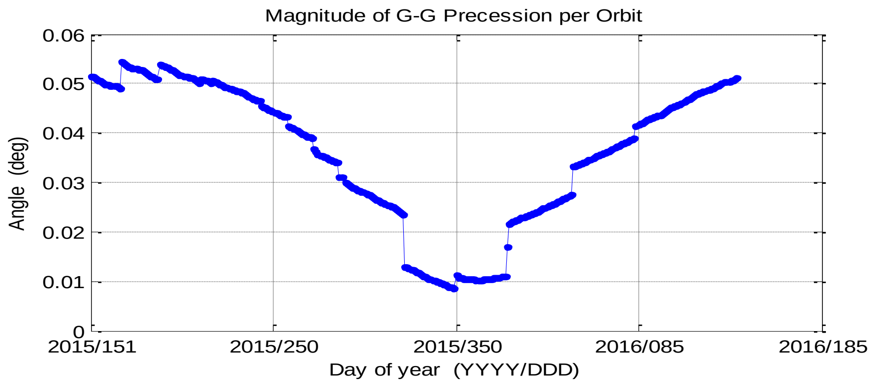
Predicted Precession of Spin Axis

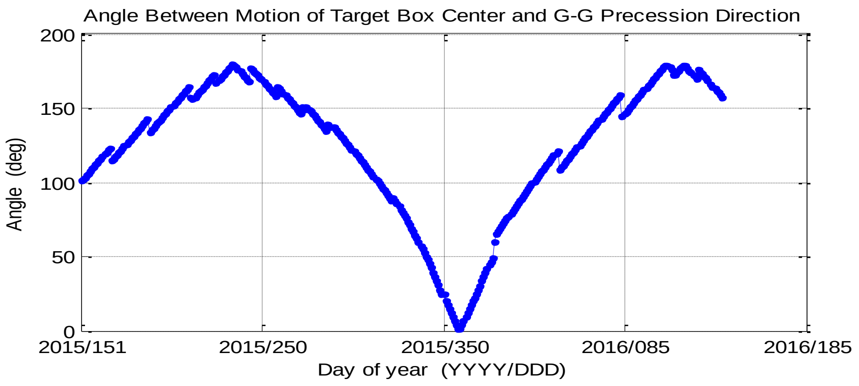
- AGS predicts GG drift of the spin axis direction
  - Early mission, after all booms deployed, drift was 0.05 deg per orbit (orbital period was close to 24 hours)
  - Plot shows accumulated drift error for 35 days with no maneuvers
  - Error in drift prediction was approximately 0.00034 deg per orbit



Seasonal Variation of Precession

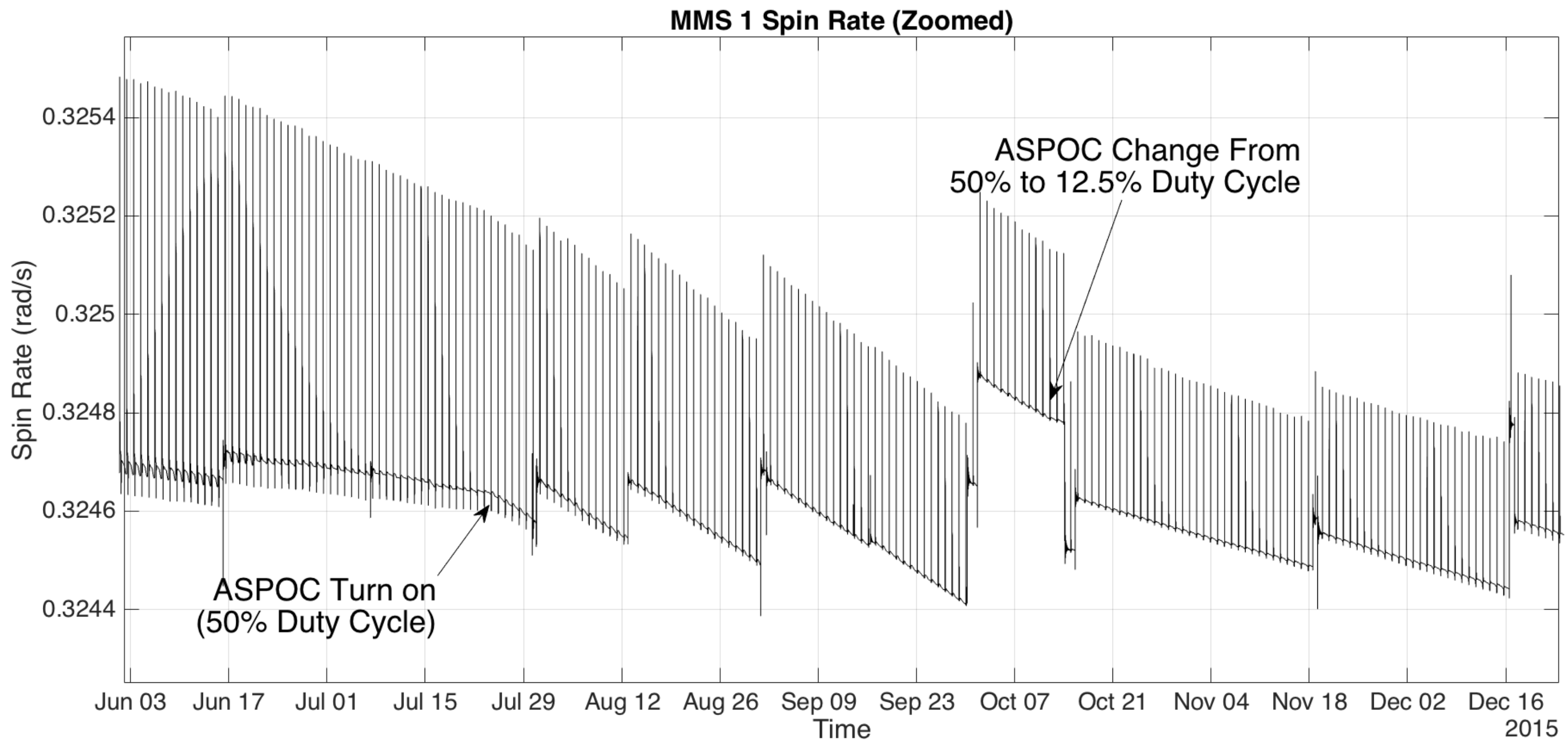
- Magnitude and direction of GG precession vary seasonally
  - Orbit normal drifted approx. 21 deg during one year, affecting GG torque
  - Target box center follows the Sun motion of one deg per day
  - Attitude maneuvers are performed every 2 to 4 weeks to stay in target box
  - Plots show seasonal variation of ***magnitude*** of precession per orbit and ***angle*** between direction of precession and motion of box center
    - GG precession is helping when ***angle*** is near zero (i.e., longer time between maneuvers), but GG ***magnitude*** is smallest then (so it doesn't help much)
    - Avg. time between maneuvers was 30 days for the months when angle was small, and was 22.5 days for the entire post-commissioning time span





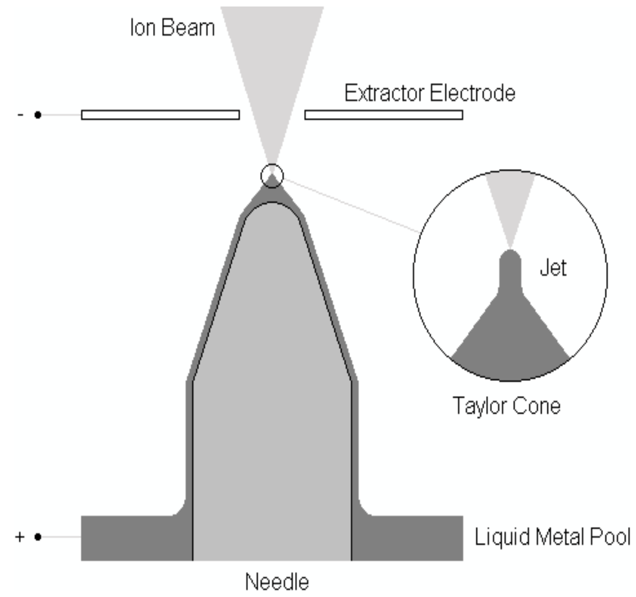
Observed Change In Spin Rate

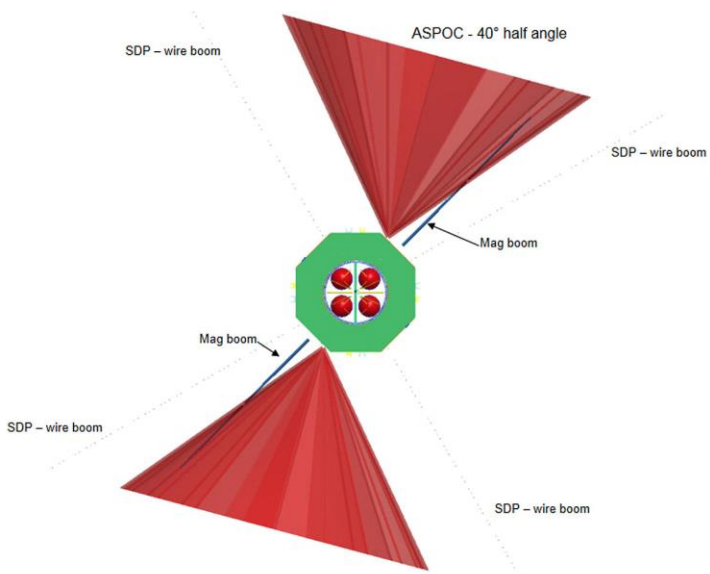
- Distinct spin rate change observed at ASPOC (Active Spacecraft Potential Control Investigation) turn on and duty cycle changes



ASPOC Characteristics

- Purpose is to neutralize buildup of positive floating potential produced by the spacecraft/environment interaction
- Strong potential created between emitter and extractor
- Indium atoms ionized and accelerated by this electric field

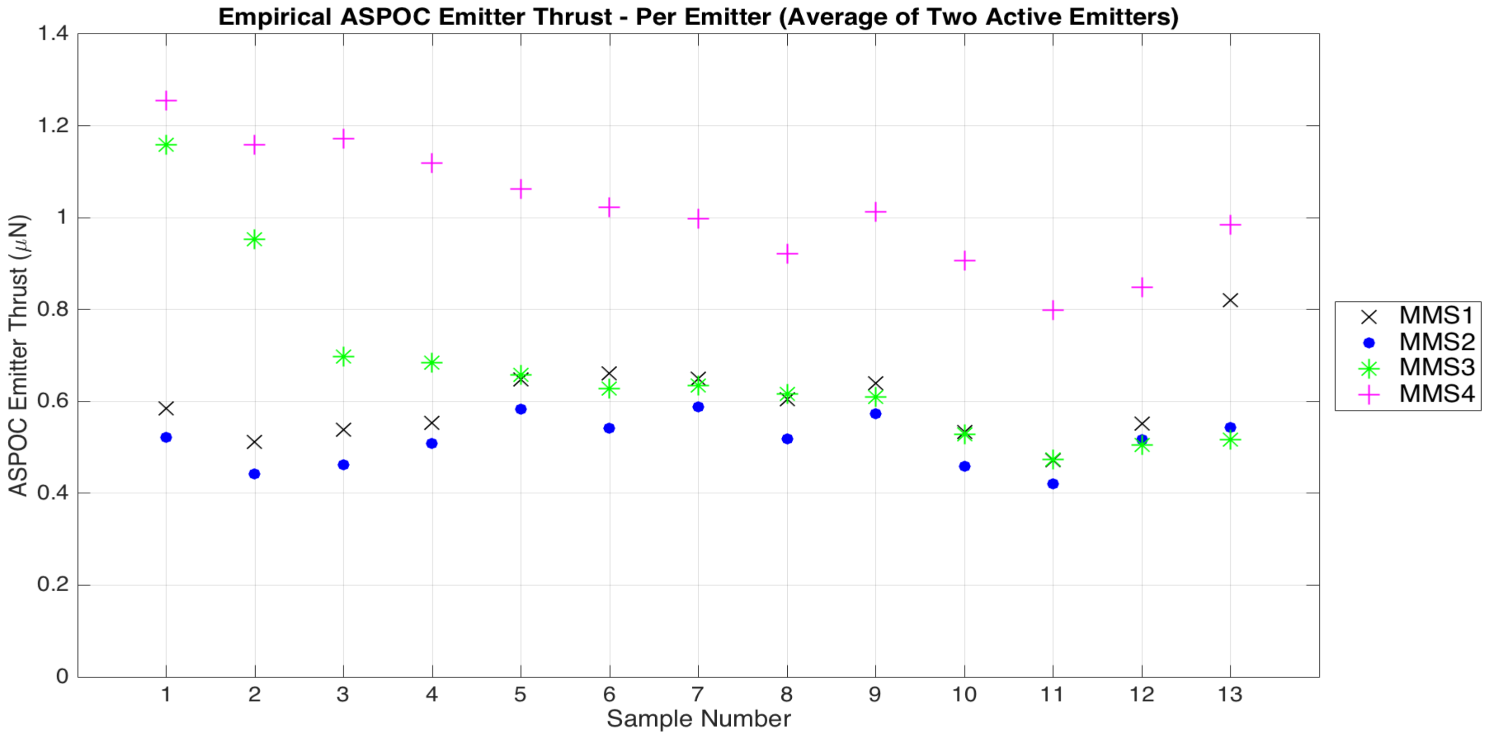




- 2 active emitters on each Spacecraft
- Location produces a coupled negative (against direction of S/C rotation) torque

Determining Empirical Thrust

- Time between maneuvers defined as a sample
- Using average deceleration, center of mass, moment of inertia, and emitter energy an empirical emitter thrust is calculated



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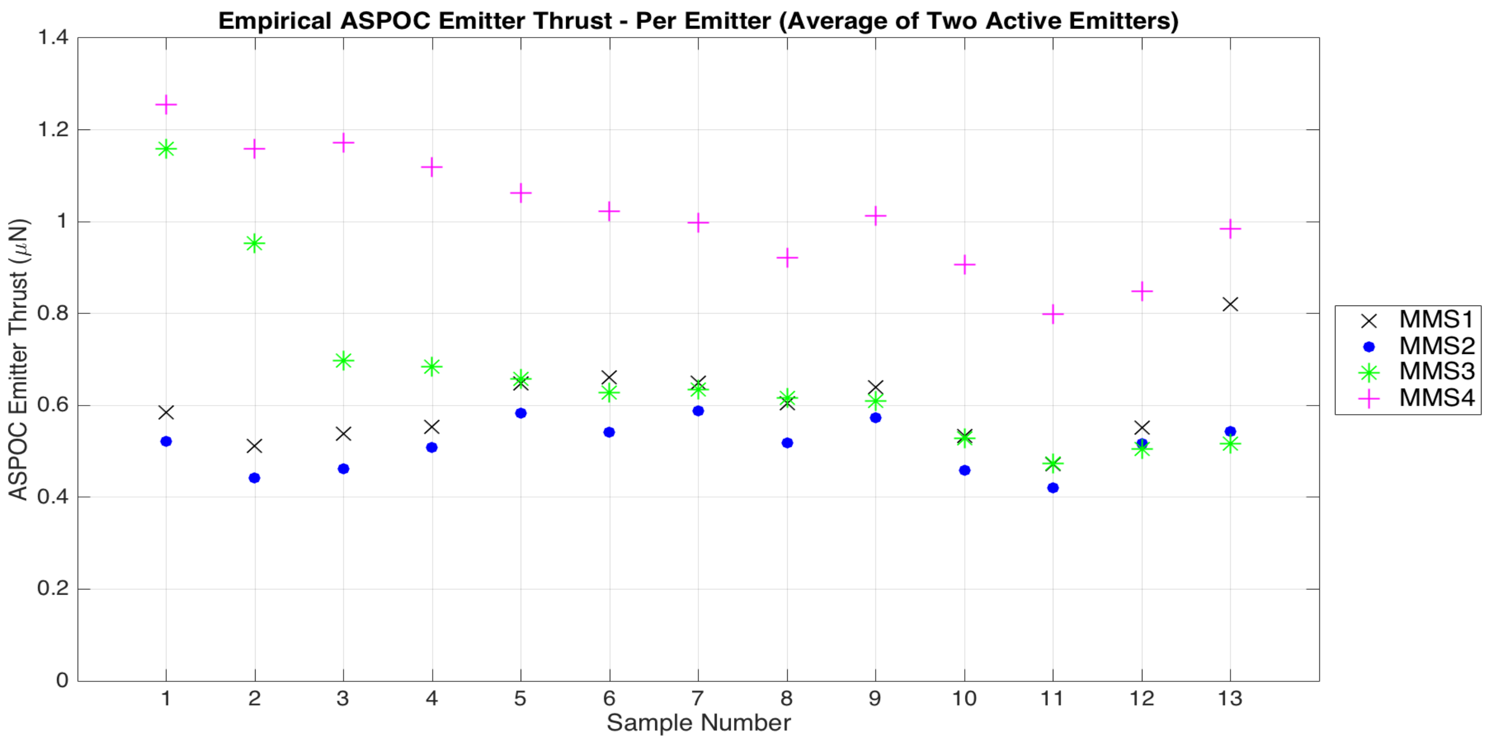


Summary of MMS4 Impact Event

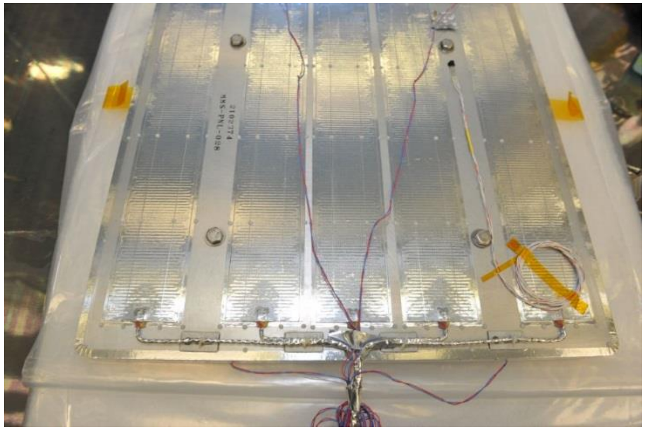
- MMS4 relevant data observations:
  - Failure of one shunt resistor
  - Accelerometers detected spacecraft disturbance
  - Star cameras “blinded” by non-star objects; reset by fault detection
  - Small attitude excursions (change in spin axis direction; nutation etc.)
  - Science instruments detected plasma around spacecraft

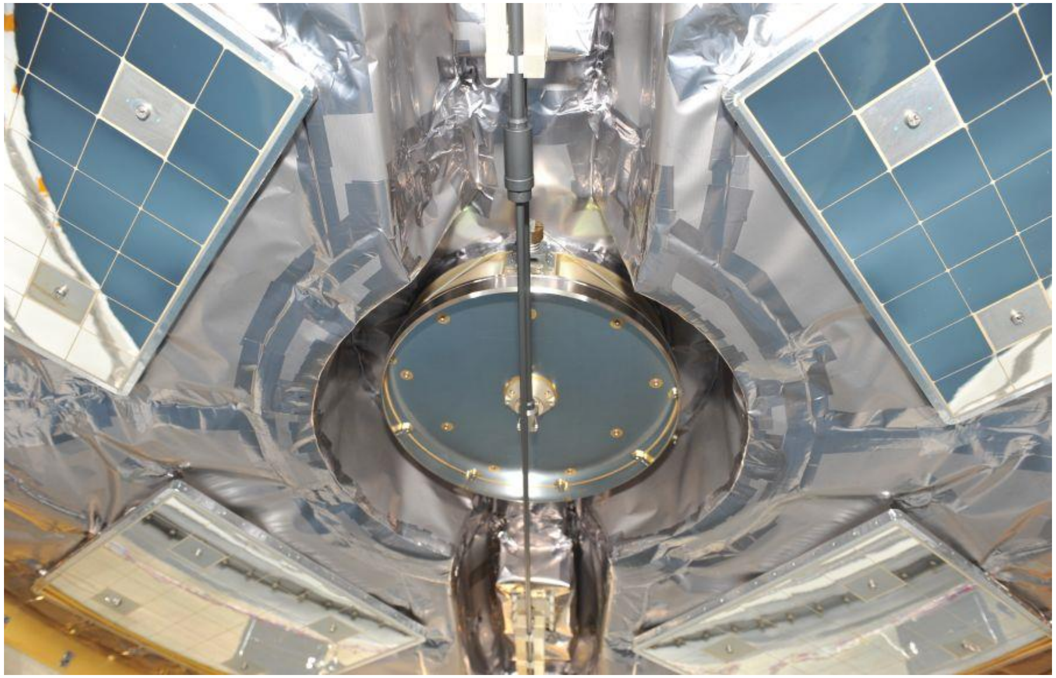
- MMS4 state at event:
  - Radius 48,176 km (7.553 R_E): 6,012 km greater than GEO radius
  - Latitude -21.2 deg: 17,403 km below equatorial GEO plane
  - 4,414 km below Ecliptic
  - Orbital speed 2.661 km/s

- Geometry of event:
  - Impact, possibly oblique, on bottom face of spacecraft

- Goals of analysis: to the (limited) accuracy possible with given data
  - Identify candidate impactor sources
  - Estimate likely approach direction
  - Estimate likely relative speed and mass of impactor
  - Estimate likely kinetic energy of initial impact

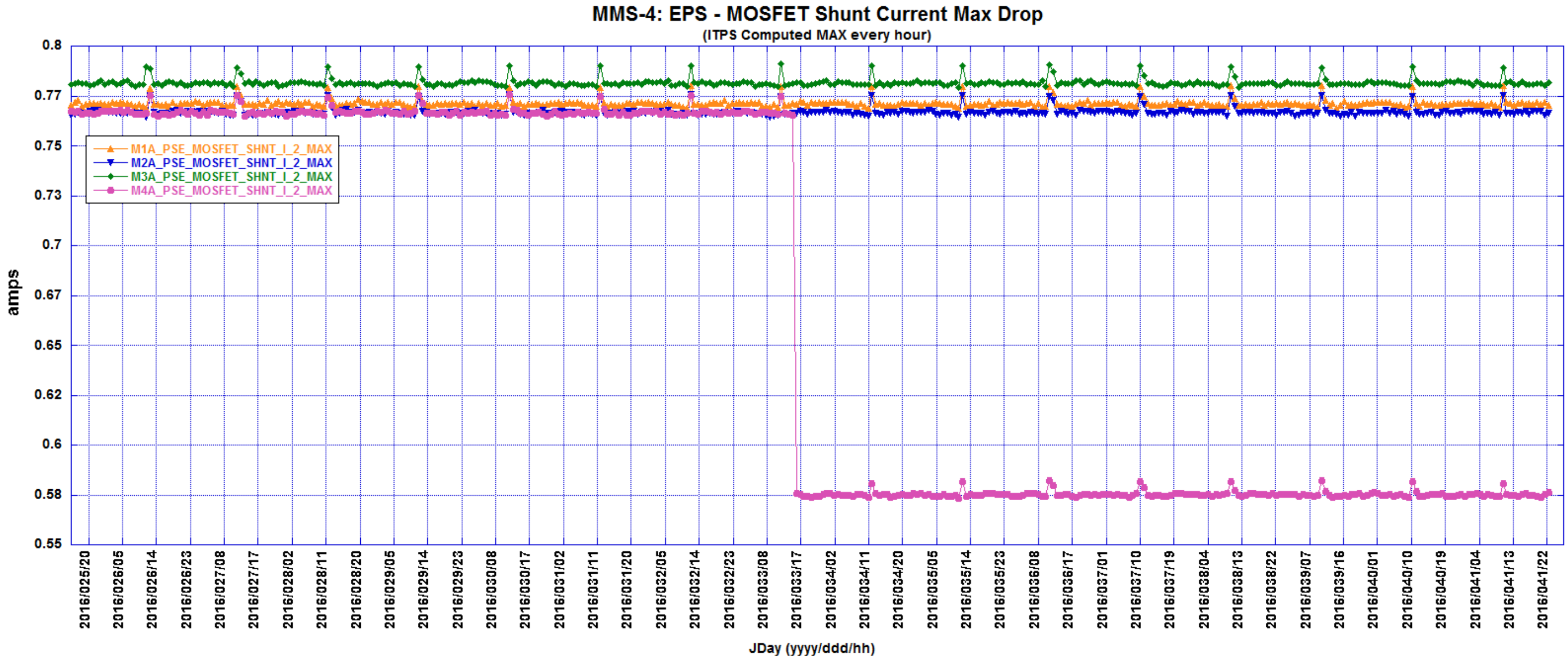
Impact Location (Shunt Resistor)





Shunt Resistor Data

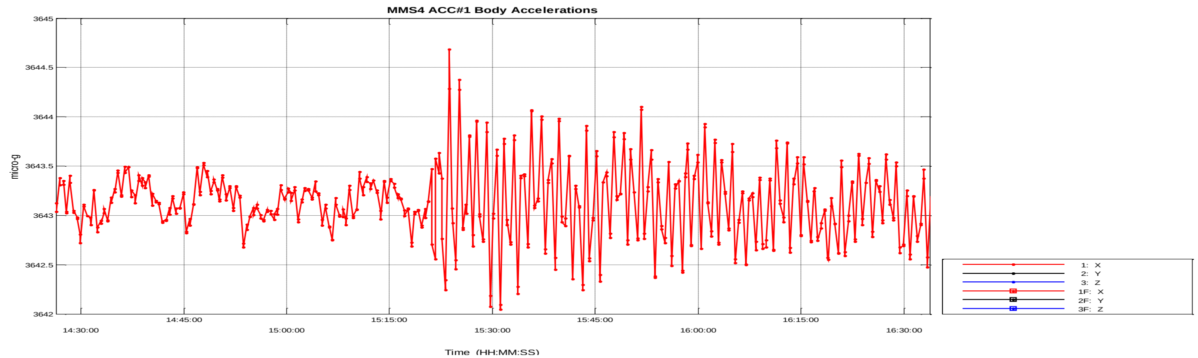
- …:
  - …
- …



Analysis Methodology

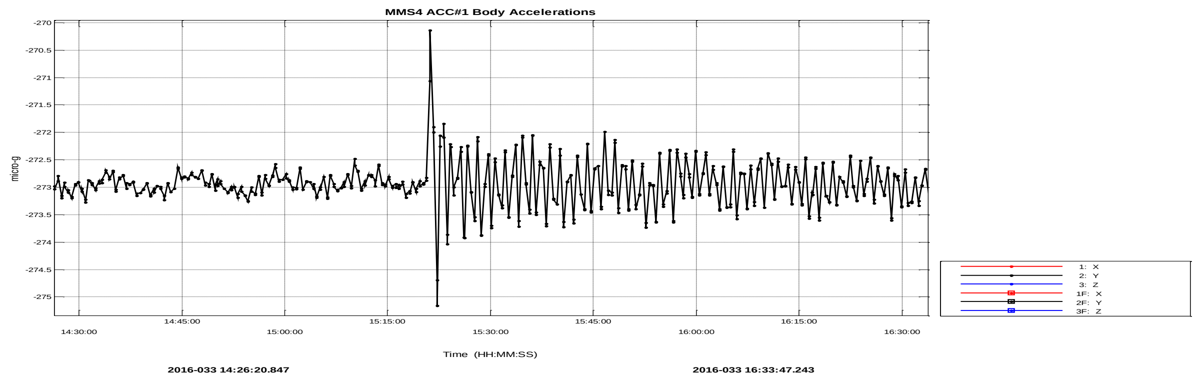
- Use relative sizes of <u>initial</u> spikes in accelerometer signals caused by event to estimate velocity direction of impactor relative to MMS
- Use change in MMS spin axis direction produced by event, together with known spacecraft angular momentum, to derive the transverse angular momentum applied to MMS by impactor
- From known impact point on spacecraft and estimated approach direction, this allows the linear momentum (mv_{rel}) of impactor relative to MMS CM to be computed
- From known position on orbit of impact, the MMS orbital velocity at the time of the event is known
- For assumed impactor population, can hence find estimated speed of impactor relative to MMS
- From the known linear momentum mv_{rel} and relative speed v_{rel}, we can then estimate the mass m of the impactor
- Use these to estimate kinetic energy of initial impact, $T=0.5mv_{rel}^2$

Accelerometer Measurements

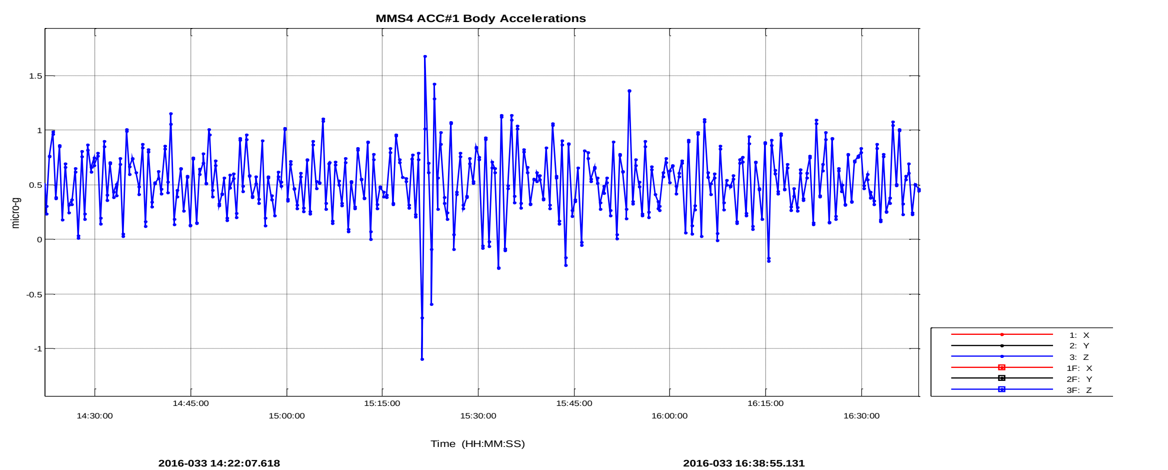


X-axis: Initial spike -0.8 micro-g

Note: All three axes only sampled every 30 s, so actual first motion may not be observed



Y-axis: Initial spike 2.8 micro-g



Z-axis: Initial spike -1.7 micro-g

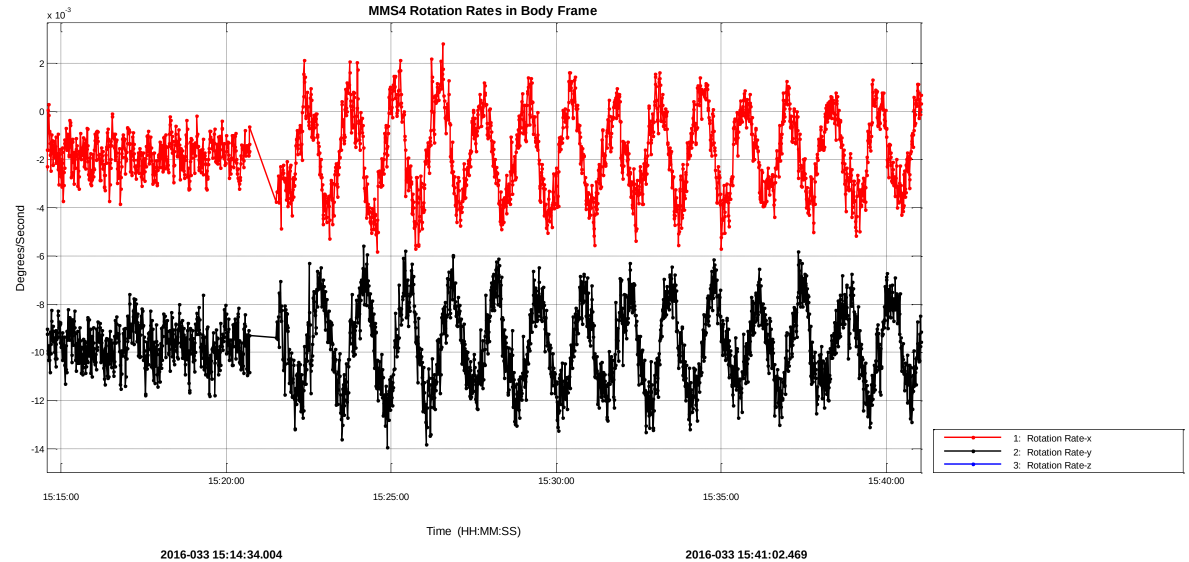
Resulting relative velocity direction estimate: 30.3 deg below spin plane

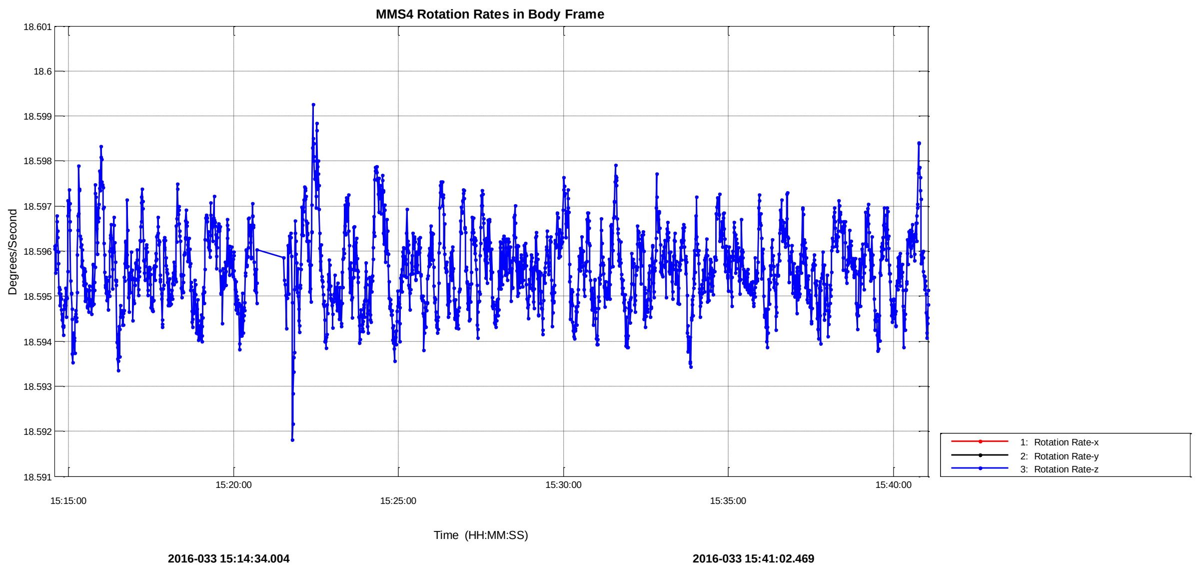
Rotation Rates, Transverse and Axial

Transverse: Nutation/boom vibration evident

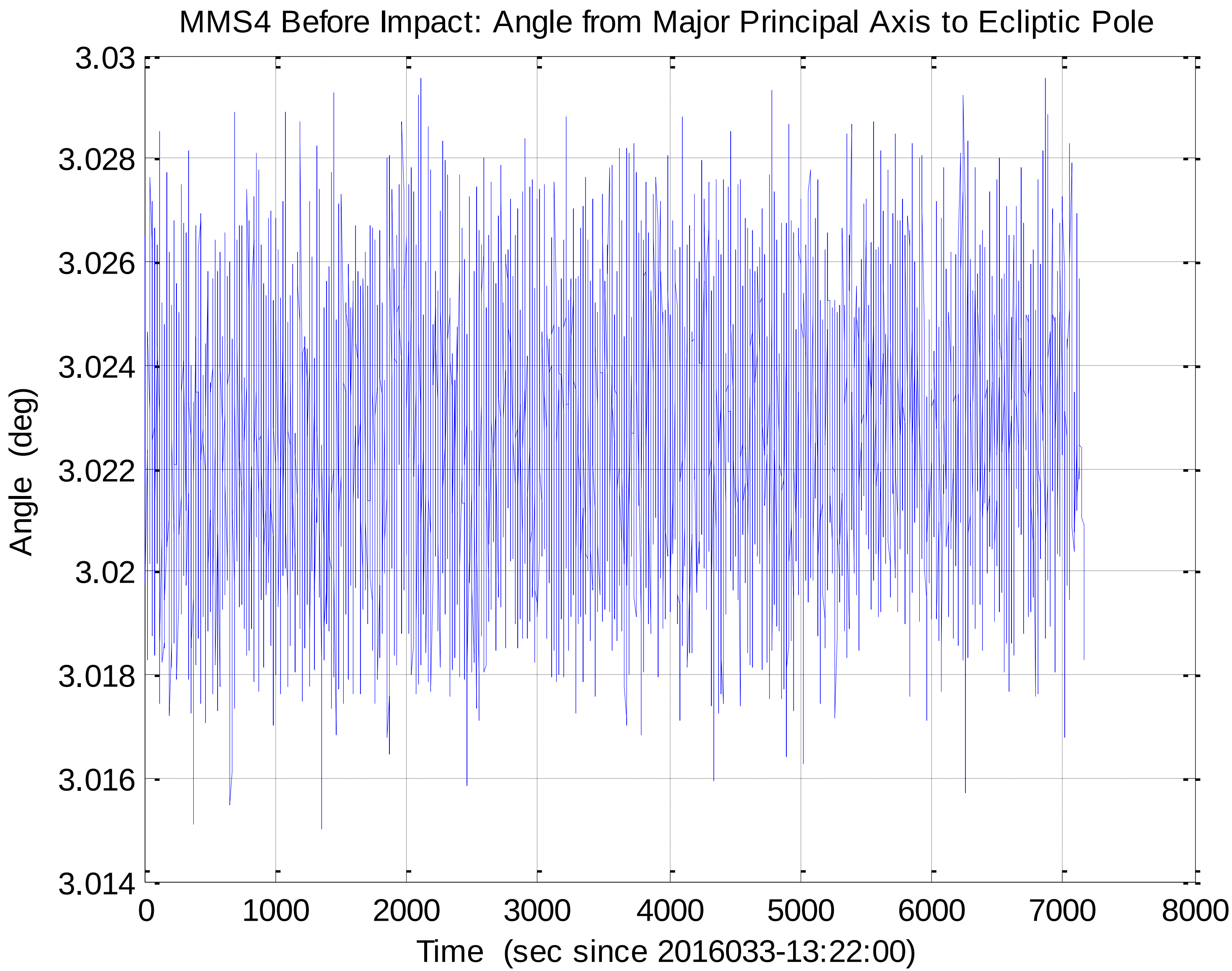
Note brief dropout resulting from star cameras being blinded/resetting

Axial: No change in spin rate evident

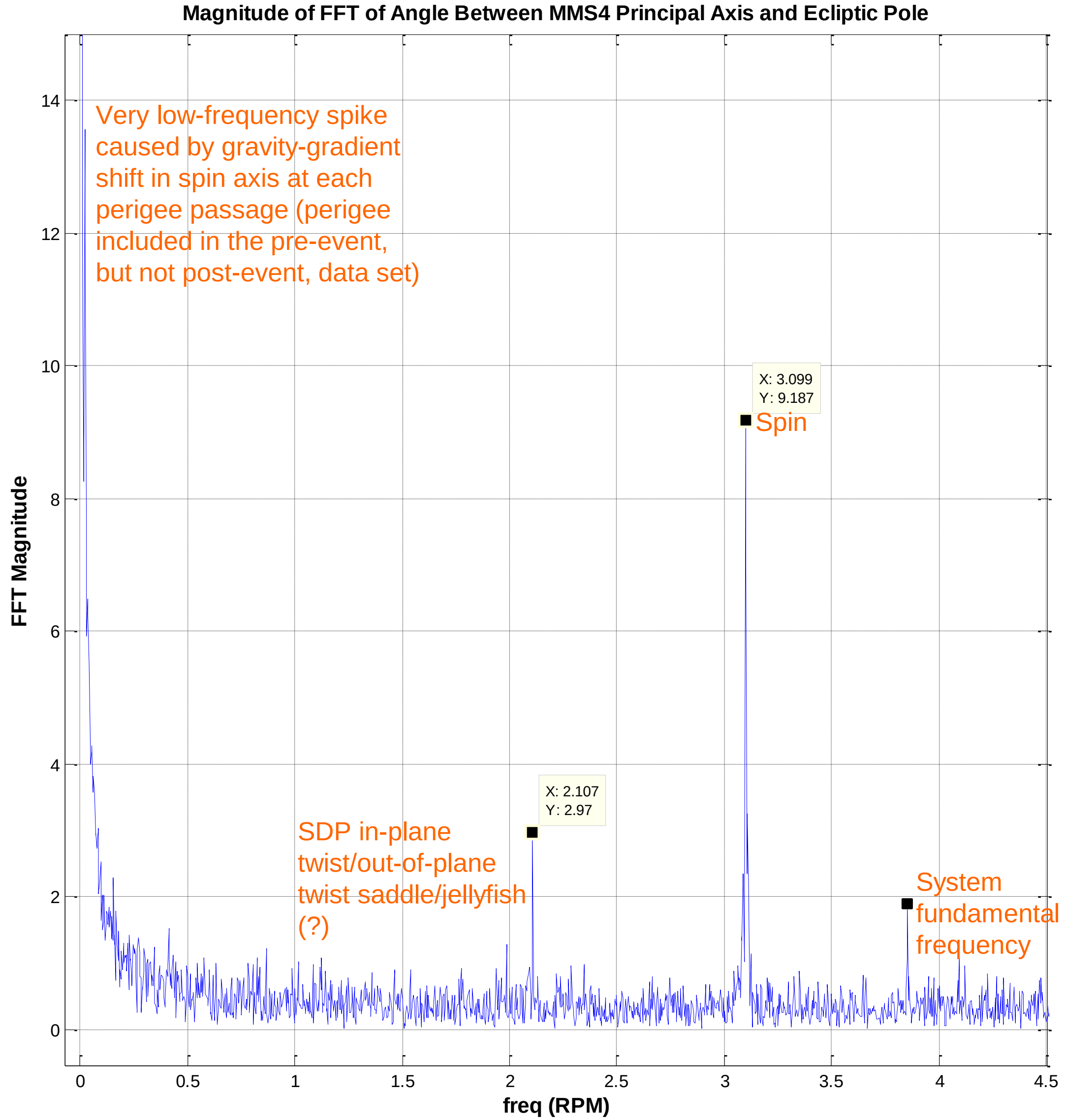




Pointing Angle Before Event

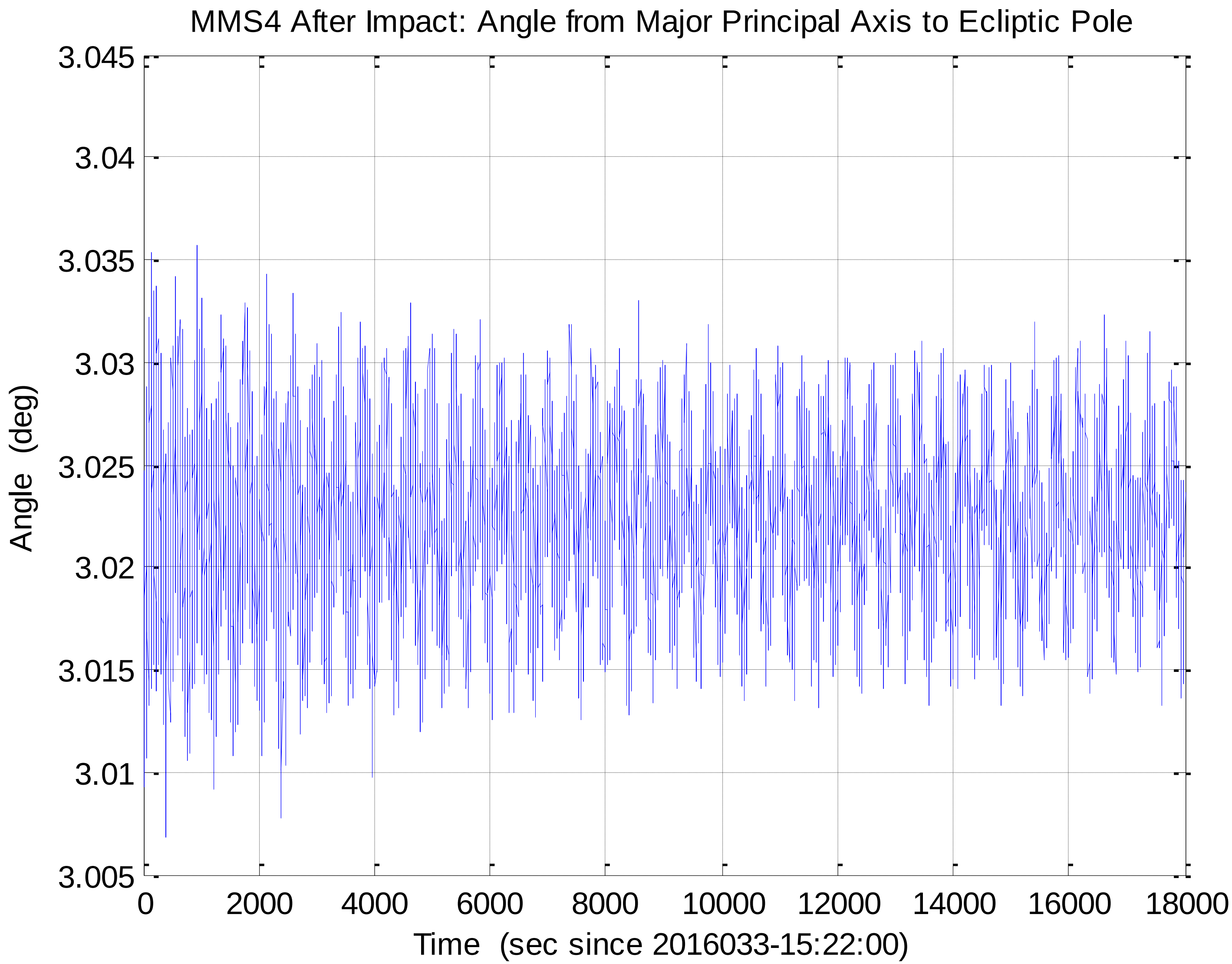


FFT of Pointing Angle Before Event



Pointing Angle After Event

Vibration with period of ~400 s dominates response



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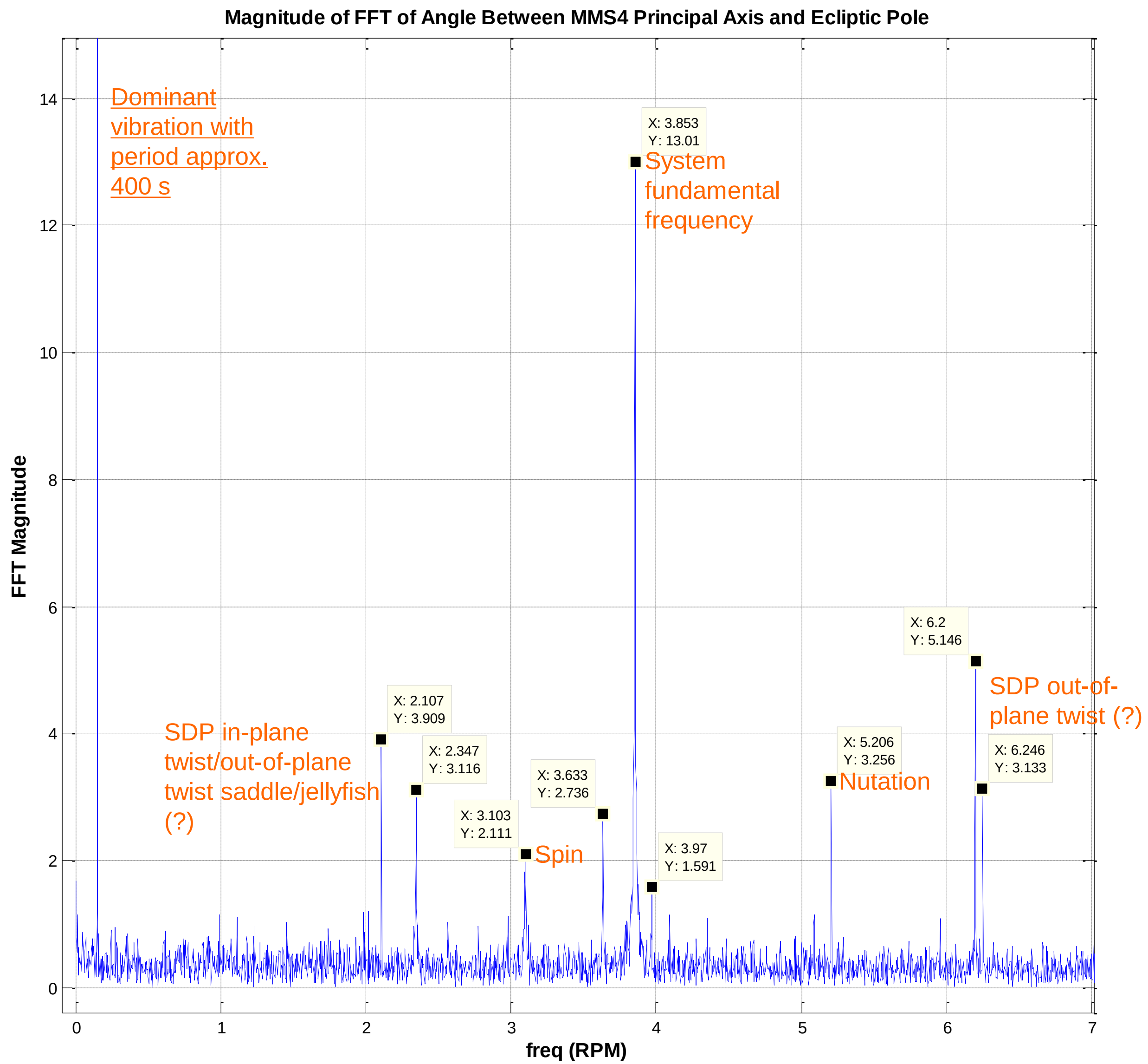
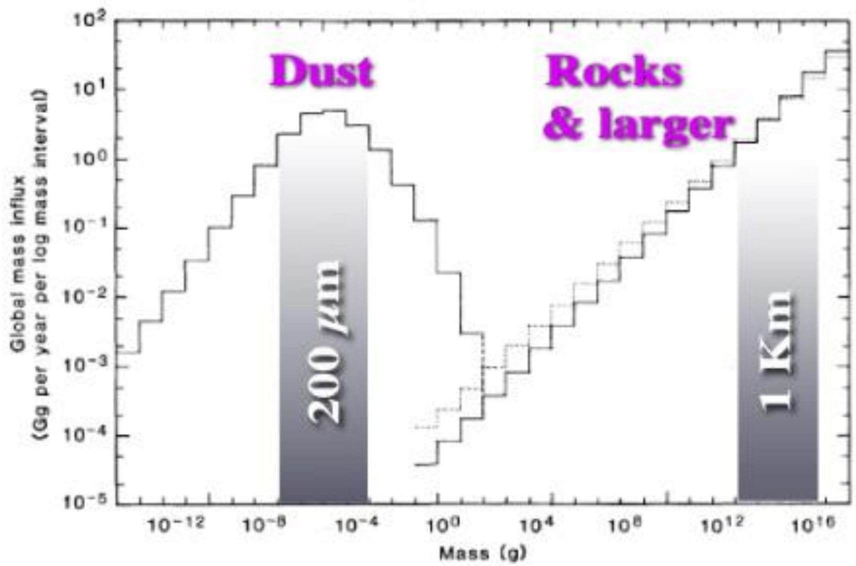


Possible Sources of Impactor - 1

- Two possible sources have been studied:
  - Micrometeoroid (dust particle)
  - Debris originating in GEO and perturbed by lunisolar gravitation plus solar radiation pressure (SRP) to point of impact

- Micrometeoroid (dust) population:
  - Overall mass range: ~ 10^{-14} to 10^{0} gm
  - Peak mass range: ~10^{-8} to 10^{-3} gm (~2×10^{-4}-0.9 mm diameter)
  - Flux tails off quickly: ~10^{-3} as high at 1 mm diameter as at 0.1 mm*



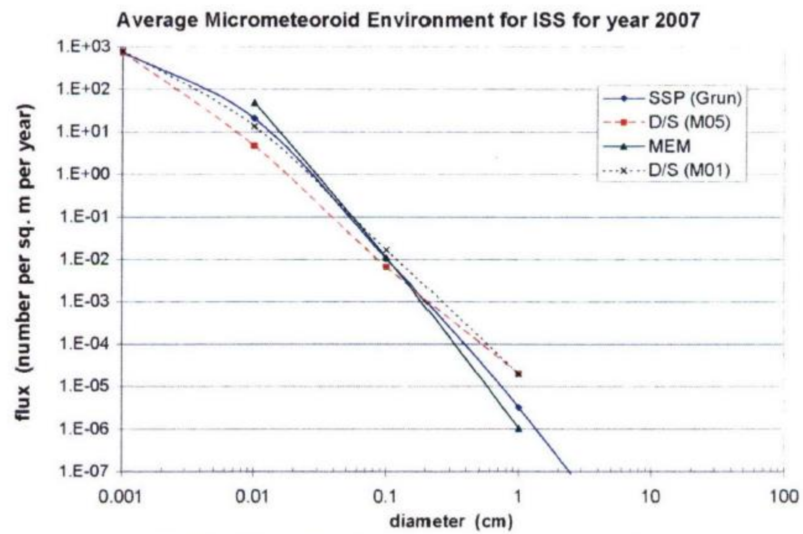


Figure 2. Micrometeoroid particle fluxes from various models.

* Fig. 2, "Micrometeoroid and Orbital Debris Environments for the International Space Station", Peterson and Lynch, 2008

Possible Sources of Impactor - 2

- Debris originating in GEO: GEO spacecraft have inclinations that oscillate between 0 and ~15 deg, as a result of lunisolar perturbations. The impact latitude of -21.2 deg exceeds this range; the impact radius was also 6,012 km above GEO
- However, objects released from GEO that have high area/mass ratios (> ~15 m^2/kg) experience significant solar radiation pressure (SRP) perturbations in eccentricity (and so radius) and inclination
- References:
  - "Long-Term Dynamics of High Area-to-Mass Ratio Objects in High Earth Orbit", Rosengren and Scheeres, 2013
  - "Long-Term Evolution of Geosynchronous Orbital Debris with High Area-to-Mass Ratios", Pardini and Anselmo, 2006
- Possible debris source: multi-layer insulation (MLI). MLI degrades in GEO. See Tedlar thin film before, after 3 years simulated GEO*:

- Representative MLI layer density 40 gm/m^2; area/mass 25 m^2/kg

* "Radiative Heat Trade-Offs for Spacecraft Thermal Protection", S. Franke, AFRL

Particle Mass, Kinetic Energy Estimates

- Linear momentum of impactor must produce observed change in spin axis direction of 0.00157 deg

- Mass, KE estimates differ for the two candidate particle sources, as a result of the different relative speeds between particle and MMS4

- Micrometeoroid:
  - "Typical" relative speed 15 km/s (very wide variation is possible)
  - Resulting estimated particle mass $8.48\text{x}10^{-3}$ gm
  - Resulting kinetic energy 953.9 J (46.6% of muzzle energy of AK-47)

- Debris of GEO origin:
  - Orbital speed of debris at impact 2.661 km/s
  - Resulting relative speed ~4.292 km/s (depends on geometry)
  - Resulting estimated debris mass $2.96\text{x}10^{-2}$ gm
  - If from an MLI layer with representative density 40 gm/m^2, this yields an area of $7.41\text{x}10^{-4}$ m^2, e.g. a square 2.72 cm on a side
  - Resulting kinetic energy 272.9 J (13.3% of muzzle energy of AK-47)

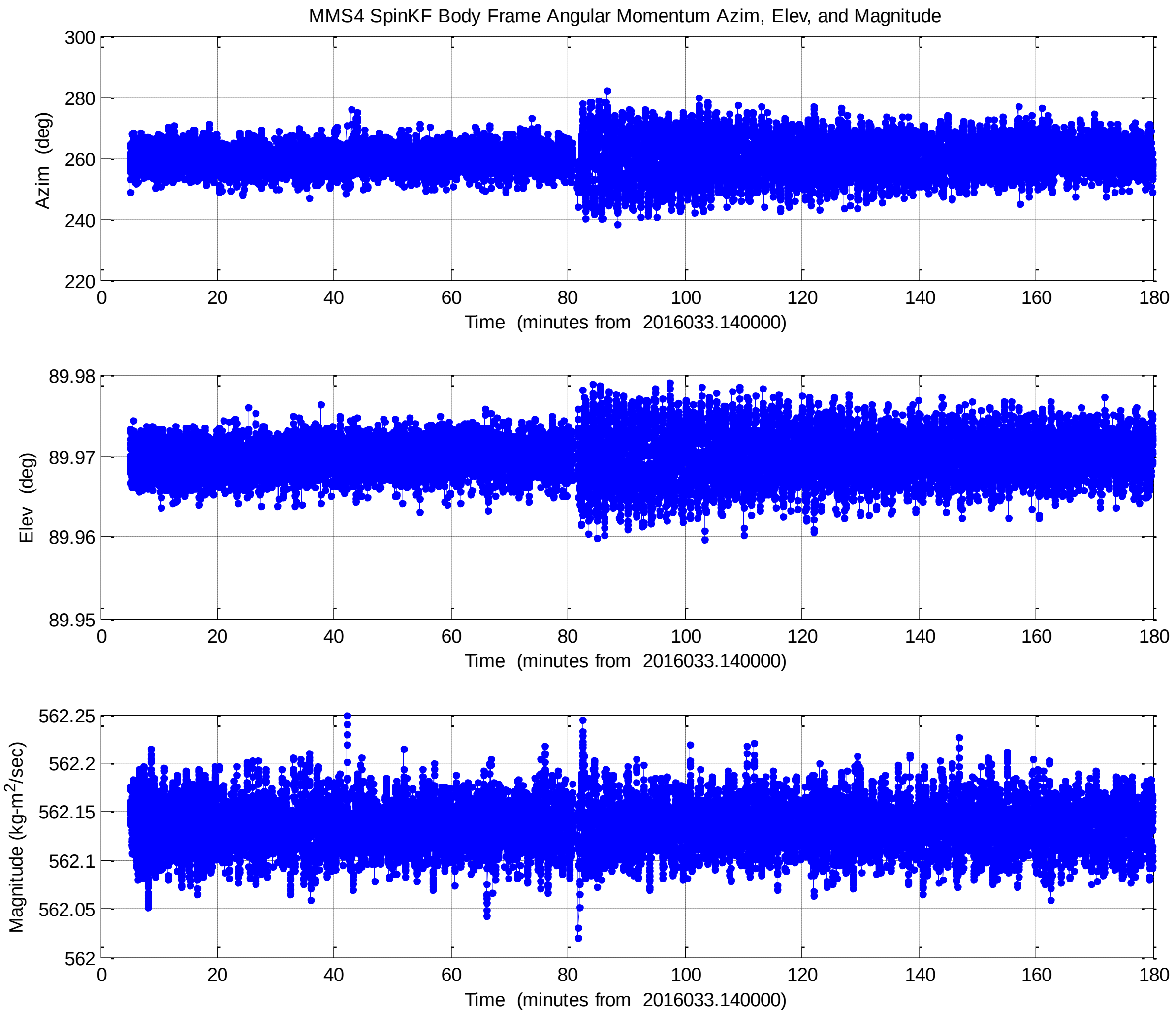
- From this analysis, it is difficult to select between the candidates. Perhaps impact dynamics analysis can lead to a determination

Backup Material

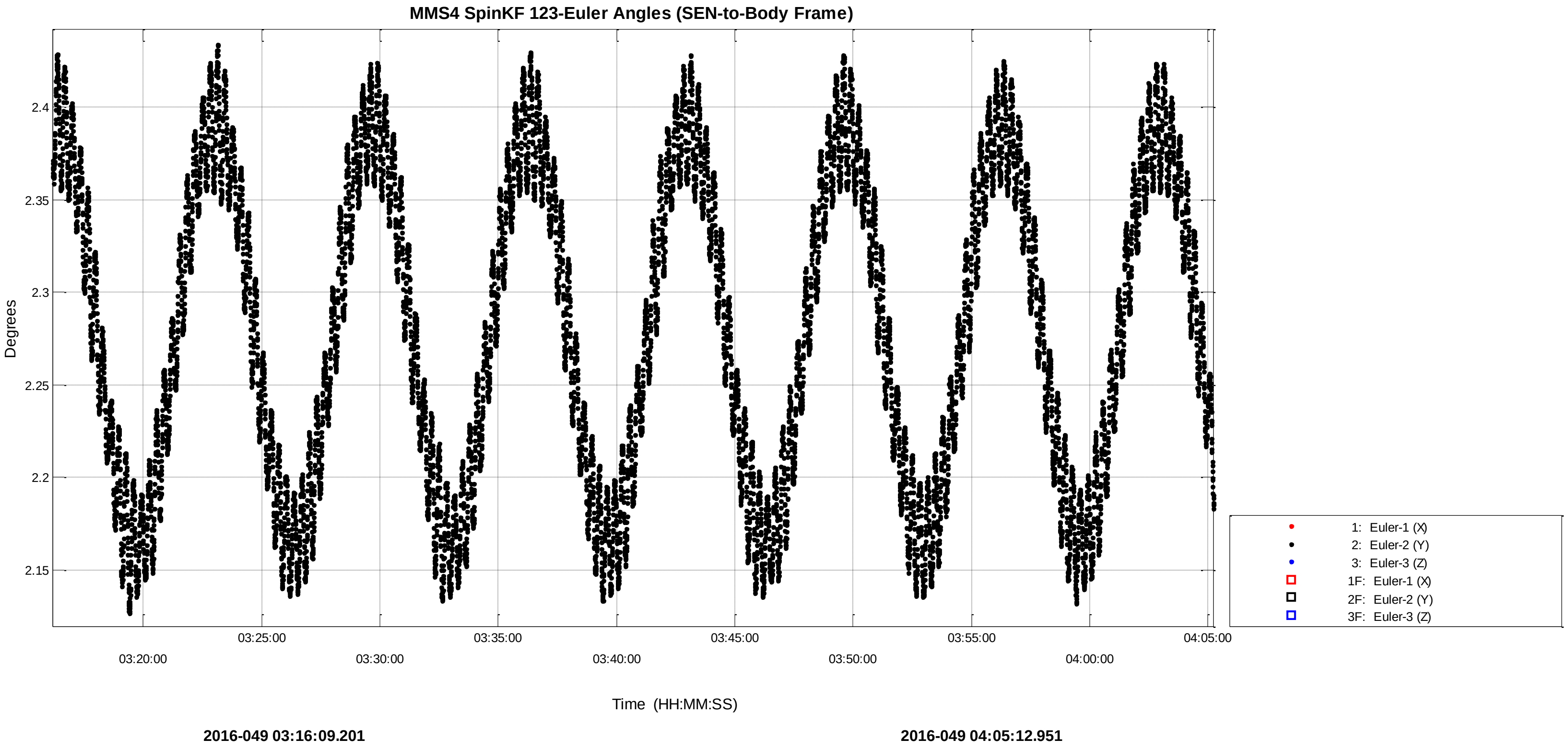
Angular Momentum

Transverse: Nutation/boom vibration evident

Axial: No change in spin rate evident. Consistent with shunt location being close to spin axis



Pointing Angle After Previous Maneuver



- Oscillation at same ~400 s period is clearly visible
- Observed after all spacecraft maneuvers
- Must be wire boom dynamics excited by thrusting/impact acceleration of central spacecraft body